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Biotechnology as a new techno-economic paradigm that will help drive the world economy and mitigate climate change

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ABSTRACT

A techno-economic paradigm embraces a whole constellation of technically and economically interrelated innovations and influences most industries and an entire phase of economic development. Its full potential to drive and shape economic growth can only be realized after far-reaching reforms have been made in the "socio-institutional frameworks" of major economies and the world economy. In close association with ICT, biotechnology – or the trio of biotechnologies: *red* (biomedicine), *green* (plant breeding) and *white* (industrial) – is now capable of such a role, although the necessary reforms remain to be made. This paper shows how far and in what sense it has reached technological maturity, and what "mismatches" between it and the socio-institutional framework are obstructing its further development and diffusion. It argues that biotechnology (green and white) is needed to play a key role in the struggle against climate change – which in turn can be expected to draw out its potential.

1. Introduction: techno-economic paradigms, concepts and cases

The concept of "techno-economic paradigm"[1] goes back to Perez (1983), who built on Dosi (1982). Both were conscious of Schumpeter, (1939) related concept of technological revolutions: a revolution involves a change of paradigm (Kuhn, 1962). The basic argument is simple: a new techno-economic paradigm appears, "embracing a whole constellation of technically and economically interrelated innovations and influencing almost all industries and an entire phase of economic development" (Freeman, 1998, p.166). A rather similar concept, more familiar to mainstream economists, is "general-purpose technology" (Bresnahan and Trajtenberg, 1995). A good example is available from recent history: what has been called Fordism had "crystallized" (become technologically mature) by the early 1920s in the United States. The key process technologies were the assembly line, built round dedicated machine tools, and continuous flow chemicals. The key products were consumer durables, motor vehicles and electro-mechanical "white goods" (refrigerators, washing machines etc.). The core infrastructure was the electricity grid and networks of roads and fuel stations. We can now, similarly, recognize Fordism's successor, information and communication technology (ICT), which had crystallized by the late 1990s in the USA and other advanced economies, completed by the arrival of the internet as core infrastructure (Freeman and Louçã, 2001).

The new paradigm has the potential to stimulate the world economy for decades through the contribution its application and diffusion can make to both supply and demand. But this impulse will initially be largely blocked by *socio-institutional frameworks* that are *mismatched* to the new paradigm. Thus the Fordist boom of the 1920s in the USA was undermined by a *macro-economic mismatch*: the split between the high-profit, high-wage Fordist oligopolies and the more competitive structures of the older, largely rural economy generated highly unequal incomes that limited the market for precisely the goods Fordism excelled in producing. In Britain and Germany, on the other hand, industrial relations and the labour market were organized in a way that obstructed the introduction of "Taylorist" mass production – *micro-economic mismatch* (Tylecote, 1992). Mismatches arise to some extent from inertia: the framework is simply out of date (Perez, 1983; Tylecote, 1992). But they are made worse by a "default" reactionary tendency in the system – to "institutional disintegration", driven, over the last half-century, by a neo-liberal faith in free markets and globalization (Mirowski and Plehwe, 2009), with more inequality (Tylecote, 1992).

We can now observe such mismatches with ICT, most clearly in the United States. Its excellence in coordinating production over distance has facilitated the relocation of low-technology operations to the low-cost bottom, at the cost of US workers (Autor et al., 2016). It has also created network economies of scale in the "tech economy" that entrench monopoly power (Economist, 2016). Meanwhile neoliberalism in the guise of conservatism has allowed the rest of the US economy to become decidedly

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[1] An equivalent term sometimes used is "technological style".

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more concentrated, less competitive and less innovative – at the expense of real wages (Galston and Hendrickson, 2018). The three tendencies combine to form a macro-economic mismatch exacerbating inequality and reducing innovation.

There is therefore no simple relationship between the appearance of a new techno-economic paradigm and the rate of growth of the world economy. There might be a period when an old paradigm is largely exhausted, at least in advanced economies (arguably, Fordism in the 1970s); a period in which a new paradigm begins to diffuse, within the constraints placed upon it by the existing socio-institutional frameworks (arguably, the ICT paradigm in the 1980s and 1990s); a period in which the tension between new paradigm and old frameworks becomes sharply apparent (arguably, the ICT paradigm in the 2000s and 2010s); and a period in which institutional reform largely liberates the potential of the now-dominant paradigm (arguably, Fordism in the 1950s and' 60 s; and perhaps ICT in the 2020s and' 30 s). If such reform is concentrated in a short period of time in much of the world economy, then it will presumably be the phase that follows which witnesses the fastest growth.

It can be difficult to define the new paradigm. In some epochs there is effectively a dual paradigm, with two distinct constellations of technologies, as with steel and electricity from the 1870s, which preceded Fordism. Tylecote (1992) argued that biotechnology would be "alongside" ICT. This was certainly not the case in 1992, because, unlike ICT, biotechnology was by no means technologically *mature* or "crystallized". On the other hand, if ICT's application and diffusion were still constrained by "mismatch", biotechnology might catch up in time for the liberation of the potential of both.

Why and how might biotechnology catch up with ICT? First, as Freeman and Louçã (2001) pointed out, the two are natural allies: the discovery activities within biotechnology are being driven forward by ICT's way with data and information. And what is DNA if not biological information? Second, biotechnology resembled software (more than hardware) in the way that once a new or modified organism was created it could be replicated at very high speed (see below.) Once biotechnology was technologically mature, the crucial issue would be the extent and durability of the mismatches between new paradigm and old institutional framework, and their effects on the diffusion of ICT and biotechnology.

This paper updates that analysis. It shows the new technological maturity of biotechnology, centred on genomics, proteomics and genome editing. It explores causes and effects of mismatches in and on biotechnology, and ways in which neoliberalism has contributed to them. The obstacles to the development of biotechnology vary among sectors. The paper first discusses those in medicine, as the sector with most activity – and most disappointment. But industrial biotechnology and bio-plant breeding might be the most important applications of biotechnology, because (it will be argued) they have a crucial part to play in the developing crisis of climate change. Their potential and likely development is explained in this context. The paper concludes with proposals for reforms that would liberate biotechnology's potential and thereby redirect and strengthen economic activity, mitigating climate change and inequality.

2. The technological maturing of biotechnology

Sociologists of technology would suggest that maturity occurs through a process of mutual shaping of institutions and artefacts (Williams and Edge, 1996). That is not what is meant by technological maturity here. The mutual shaping of institutions and artefacts will take place during the life of the paradigm. What are, minimally, mature at the beginning are rather the main *techniques*. Thus the technological maturing of biotechnology requires the availability and cheapening of knowledge about living organisms at the molecular level, and the capacity to intervene precisely and cheaply at that level. The cost of both is falling fast. "A genome that cost $100 m to sequence in 2001 can today be sequenced for roughly $1,000″ (Murgia, 2017). And the arrival of CRISPR-Cas9 since 2012 has brought increasingly precise, cheap and quick genome "editing".

To be clear in our understanding of the term:

> "Genome editing" is the practice of making targeted interventions at the molecular level of DNA or RNA function, deliberately to alter the structural or functional characteristics of biological entities…. the concept of genome editing is not limited to genes… [it] also includes making alterations to non-coding regions of genomes and to epigenomes (in order to modify whether all or part of the genome is active or silent, and to "tune" the level of activity). (Nuffield Council on Bioethics, 2016, pp.1.1-1.3.)

Early genetic modification, dating from the 1970s, was untargeted: a gene was inserted into a genome, somewhere, hoping that it would work there as it appeared to work in its native organism. The first widely effective targeting technologies date from 2005 – zinc finger nucleases (ZFNs) – and 2010 – transcription activator-like effector nucleases (TALENs). In the course of two or three years from 2012 they were almost completely superseded, worldwide, by CRISPR-Cas9, borrowed from a system developed by bacteria for dealing with viral attack. "CRISPR-Cas9 works by causing a targeted DNA break but it is possible to replace the DNA cutting activity of Cas9 with other activities, for example… to switch selected genes off or on without altering their sequence" (Nuffield Council on Bioethics, 2016, p.1.18). It is the quickest, cheapest and most reliably targeted method, and is being constantly improved on all three dimensions.

The genome guides the manufacture of proteins within the cell. One of the main bottlenecks now is knowledge of protein structures: *proteomics*. In drug design, for example, that is crucial: "Almost all drugs work by binding to a particular protein in a particular place, thereby altering or disabling that protein's function. Designing new drugs is easier if binding sites can be identified in advance. But that means knowing the protein's structure" (Economist, 2017a). Or, to quote the mantra of structural biologists, exaggerating only slightly, "structure is function".[2] About 120,000 types of protein had known structures, as of January 2017 – a large number, it might seem, but they belong to fewer than a third of the 16,000 known protein families. About 30,000 of these proteins are human (Economist, 2017a).

A new technique called protein-contact prediction has been accelerating the process of identifying protein structures, but is directly applicable mainly to bacterial proteins – useful enough, given their negative role in disease and their positive role in industrial biotechnology and as sources of transgenes (see Section 5.1). "Deep learning" is now being employed to help make inroads into the remainder, including human proteins. "Deep learning employs pieces of software called artificial neural networks to fossick out otherwise-abstruse patterns… such programs should be able to spot correlations between three, four or more amino acids, and thus need fewer related proteins to predict structures" (Economist, 2017a).

But the 2017 Nobel Prize in Chemistry was awarded to Jacques Dubochet, Joachim Frank and Richard Henderson for an even more important technical development, worked on for decades, and also drawing on advanced software, which has now (to quote the award citation) "moved biochemistry into a new era": cryo-electron microscopy. "For decades, biologists have used X-ray crystallography – blasting X-rays at crystallized proteins – to image biomolecular structures. But labs are now racing to adopt the cryo-EM method, because it can take pictures of proteins that can't easily be formed into large crystals" (Cressey and Callaway, 2017). Which is to say, most proteins.

Knowledge of protein structures is not *quite* the River of Jordan – one last river to cross before the "promised land" of rational drug design (and rational design of plants/animals/fungi/bacteria/viruses) opens

[2] Structural biology is the study of the molecular structure and dynamics of biological macromolecules, particularly proteins and nucleic acids, and how alterations in their structures affect their function. Structural biology incorporates the principles of molecular biology, biochemistry and biophysics. (www.nature.com/subjects/structural-biology, accessed 15 Feb. 2018).

out before us. "Most diseases are triggered by multiple targets operating in unknown (and possible unpredictable) sequences" (Gittelman, 2016, p.1581) and this may often apply to the functions of organisms: proteins operate in combination and interaction with others. But there are other ways of understanding their effects: for example, CRISPR can be used to disable a gene, to observe what happens. This sort of experiment is now available to DIYbio (do-it-yourself biology).

DIYbio began around 2005, inspired by the example of electronic hackers in software in Silicon Valley in the 1960s; thus the terms "biohackers" for its exponents and "wetware" for its outputs. DIYbio also has roots in iGEM, a successful annual synthetic-biology competition for undergraduates. Biohackers view DNA as a form of software that can be manipulated to design biological processes and devices. Their key tool – like the 3D printer beloved by "makers" – is the PCR (polymerase chain reaction) machine, which can identify a specific segment of DNA and make multiple copies of it. By 2014 one group had developed a simple PCR machine that cost only $600 (Economist, 2014b). They were busily developing new cheap open-source versions of other tools. They have made impressive progress both in cheapening equipment and finding new ways to share it (De Lorenzo and Schmidt, 2017). By February 2018 a whole DIY Bacterial Gene Engineering CRISPR Kit was on sale for US$159.[3]

Of course DIYbio

> is greatly facilitated and accelerated thanks to digital… All the sequenced genes are available on NCBI, all the proteins on UniProt. A lot of patient information is available, take a look at the British NHS… Data exploitation is now much easier. In a few minutes, you can find new protein interactions, compare your sequenced gene with all existing genes…You can manage your lab via your smartphone… Instead of using paper notebooks, you can now use solutions such as LabFolder to stock all your experiments and data, available everywhere in the world and share them with other people. Instead of printing your gel, just take a picture with your iPhone. No need to scan your protocol or to type it again, just write it directly in your digital notebook and share it with your colleagues. (Hemme, 2015)

Using CRISPR to disable a gene and carefully observing the consequences is akin to the "experimental parameter variation" which dates back to John Smeaton's work on waterwheels in the 18th century (Tylecote, 1992, Chapter 2) and the propeller tests conducted at Stanford University by W.F. Durand and E.P. Lesley from 1916 to 1926 (Rosenberg and Steinmueller, 2013). Engineers such as Durand and Lesley were accustomed to the limitations of scientific knowledge, and such responses in the aggregate constituted *mass experimentation*, which allowed technological progress to proceed ahead of scientific knowledge. DIYbio may offer a speeded-up and much expanded version of such experimentation, which by contributing quickly to "big data" may help advance the science.

3. Biopharma and the obstacles to a biotech revolution in medicine

We can distinguish between three key applications of biotechnology (Langeveld et al., 2010):

- Biopharmaceuticals and other applications to medicine (*red* biotechnology);
- Plant breeding and other applications to agriculture, pisciculture etc. (*green* biotechnology);
- Industrial biotechnologies (e.g. for fuels or materials) (*white* biotechnology).

The first two deal with open and complex biological systems, which make the process of getting new knowledge more difficult in itself and more open to public opposition. Red biotechnology has hitherto been the most active area, and within it biopharma, so much so that when Hopkins et al. (2007) asserted "The Myth of the Biotechnological Revolution", biopharma was the only area they discussed. They were right that much had been promised and little had by that point been achieved. Gittelman (2016) offers an explanation. The biotechnology revolution (in medicine at least) was expected to be driven by a linear model of science-push innovation; so clinicians were seen as subordinate. Venture-capital-backed start-ups based on university research (on the "tech" model) seemed appropriate. Unfortunately, the human body has proved too complex for this approach. Clinicians need to be heavily involved from early in the discovery phase. They have a different research paradigm from the basic researchers in molecular biology, a paradigm embodying "a fundamentally different epistemic culture" that needs to be understood and respected. Not by chance, then, "inventions by teams of scientists at Academic Medical Centers are more likely to be licensed to firms when they are led by clinicians, over and above the composition of the team" (Gittelman, 2016, p.1583). Summing up: "Medical research closely utilizes scientific knowledge but requires institutional and organizational arrangements that support, rather than conflict with, its own distinct logic of discovery" (p.1584).

Another institutional failure is that of government, to see how best it can contribute to the advance of biopharma. This is somewhat ironic: in the USA the National Institutes of Health are given the lion's share of federal non-defence research and development (R&D) spending (Tassey, 2007), but the NIH lack "an explicit disaggregated R&D model with appropriate… progress assessment methods to both guide funding and make missing elements of generic technologies more visible… [leading to] inadequate investment in generic technologies before substantial private-sector investment in attempted innovation occurred" (Tassey, 2007, p.121). Inadequate investment in generic technologies has been noted generally, as has an overall decline in public sector R&D spending, with adverse implications for long-term innovation (Archibugi and Filipetti, 2018). Neoliberal ideology (Mirowski and Plehwe, 2009) lauds the successes of private enterprise in high-technology industry – financed by venture capital; Mazzucato (2013) and Weiss (2014) point rather to the role of the Federal Government, which provided most of the early-stage finance and indeed helped to set up the venture capital industry. The introduction of the internet could be seen as one last great act of state entrepreneurship before the ebb tide of neoliberalism prevailed.

Progress in biopharma is delayed also by the malfunctioning of the patent system. Neoliberalism can be given credit for "incentivizing" private investment in innovation by the extension of intellectual property rights. But while A's intellectual property is protected by its patents, they may block the winning of new knowledge by B: patent protection in emerging areas tends to be too broad (Nuffield Council on Bioethics, 2012, Chapter 9). At the same time, patent protection tends to be too short: "much, if not all, of the 20 year patent term for those patent applications filed in the early stages of emerging biotechnologies is likely to have been consumed by the time that the technology is commercialised"[4] (Nuffield Council on Bioethics, 2012, p.188). While pharma products can have their patent term extended to 25 years, that does little more than compensate for the onerous regulatory requirements in this sector (Nuffield Council on Bioethics, 2012).

The heavy burden of R&D and marketing overhead, and the short time enjoying patent protection, drives firms to charge "what the market will bear" – a monopoly price far above the marginal cost of production and distribution, and in fact above what part of the potential market will be able and willing to pay (Nuffield Council on Bioethics, 2012, Chapter 9). Monopoly pricing is a crude way of extracting social value from a drug: on the one hand, some who receive the drug find it worth more than was paid for it; on the other hand, those who did not receive it, but would have done so had the price been no more than marginal cost, represent an unexploited source of social value. This provides the opportunity for large-scale buyers

[3] http://www.the-odin.com/diy-crispr-kit. Accessed 13 Feb. 2018.

[4] For example, the basic patents in RNA interference (RNAi) date from around 2001. As of September 2017 no commercial product based on RNAi technology had been authorised, although one seemed close (Lundin, 2011; Gill, 2017).

of drugs, such as the British National Health Service mentioned by Hemme above, to negotiate on the following lines:

> Provide us with all we wish to use of your drug, at marginal cost price in the first instance. We shall conduct health impact studies year by year, taking advantage of our plentiful data and epidemiologists, and economies of scale – and increasing those economies by sharing data with our peers. If your drug proves as effective as you say, we shall pay you an extra lump sum which will more than match the profit you would otherwise have got – and you may quote our health impact study results round the world. That will allow *you* to save a large part of your marketing budget, which currently exceeds your R&D budget; or to sell more to other customers. And *we* shall get to treat *all* of our patients who can be expected to benefit, more than marginal cost, from your drug. (Distilled from Nuffield Council on Bioethics, 2012, Chapter 9)

But this opportunity has not yet been taken.

Another flaw in the institutional framework relates to the transmission and analysis of data. ICT must be of great assistance in this. But the unregulated market does not encourage the transmission of a very important sort – clinical data on the efficacy and safety of innovative treatments. Indeed private firms have an incentive to conceal unfavourable clinical data, at least on efficacy. Unpublished clinical trials and abandoned projects – including the huge number of compounds that have failed in clinical trials – are untapped stores of data that would be of great value to the research community. This data could be made compulsorily available, no doubt with some delay (Gittelman, 2016).

There are thus a number of serious mismatches between the institutional framework relating to medicine, and the needs of biotechnology as applied to it. They can and should be rectified, but even without that, the power and precision of the new techniques is now such that real revolution in biomedicine may not be far away. And their reach is global even if much of the early work was funded by the US National Institutes of Health. One example: an Oxford (England) oncologist is developing a new "virotherapy" that uses an engineered virus to find and kill cancer cells but leave others unharmed. "The idea that viruses might kill cancer cells has long been entertained… 'Progress has really accelerated … since we learned how to genetically modify viruses to make them effective anti-cancer agents but safe to normal tissues'… [moreover] the virus… can turn the cancer cell into a drug factory", with potent anticancer proteins, or "biologics", encoded within the viruses at the DNA (or RNA) level (Garth, 2017).[5] For now, it is biologic pharmaceuticals produced in a more conventional way that dominate biomedicine – not just in their development, but also in their diffusion. Between 2011 and 2016 global revenue from biologic drugs rose by 70% to $232bn; between 2006 and 2016 their share of the world pharma market rose from 16% to 25%. In 2016 50% of the US Food and Drug Administration's new chemical entity approvals were for biologics (Quintiles IMS, 2017).

The other two biotechnologies, white and green, industrial biotechnology and the breeding of plants and other organisms, have lagged behind biomedicine. If they catch up, it will be because they stand greatly to gain from, and contribute to, humanity's forthcoming struggle against climate change. We shall set the scene for them, therefore, by explaining that context.

4. The struggle against climate change and the need for bio-retrofitting

4.1. Policy delay and the consequent urgency to cut emissions

The Paris conference on climate change in 2015 was successful in getting participants to commit to the ambitious goal of limiting warming below 2 °C over pre-industrial temperatures, indeed if possible keeping it below 1.5 °C above pre-industrial levels – which would be only 0.4 °C over the 2016 level. It was much less successful in getting specific policy commitments that might make at least the upper limit achievable. As of November 2017, the estimate of Climate Action Tracker (2017) was that temperatures would by 2100 reach about 3.4 °C above pre-industrial levels under current government policies – those policies including subsidies to fossil fuels of $260 bn per annum, nearly twice the subsidy to renewables (IEA, 2017).

What policies might be sufficient to achieve the goal of 2 °C, was set out in *Perspectives for the Energy Transition* (IEA/IRENA, 2017, pp.7–8):

> Limiting the global mean temperature rise to below 2 °C with a probability of 66% would require an energy transition of exceptional scope, depth and speed. Energy-related CO_2 emissions would need to peak before 2020 and fall by more than 70% from today's levels by 2050. ….The 66% 2 °C Scenario would require an unparalleled ramp up of all low-carbon technologies in all countries. An ambitious set of policy measures, including the rapid phase out of fossil fuel subsidies, extensive energy market reforms, and stringent low-carbon and energy efficiency mandates would… need to be *introduced immediately and comprehensively across all countries… with CO_2 prices reaching up to US dollars (USD)190 per tonne of* CO_2. (Emphasis added; the $190 price is for OECD countries in 2050, but even by 2030 they would be charging $120, and "major emerging economies" $90.)

The current political impossibility of such actions may be judged by the fact that as of 2017 the European Union was almost alone in charging anyone for CO_2 emissions. Its Emissions Trading System provides permits for major emitters of carbon dioxide, most of them without a charge; those who must pay have been charged less than €10 per tonne since 2011 (as of December 2017; Evans, 2017). The Paris Agreement did yield expressions of intent to change policy from 187 countries, which allowed the International Energy Agency to formulate a rather optimistic New Policies Scenario, which "describes where existing policies and announced intentions might lead the energy system" (IEA, 2017, Executive Summary p.1). Fig. 1 shows the gulf between the two scenarios, up to 2050.

4.2. More haste, less speed: problems of "fixed emissions" in carbon mitigation

As each year passes without radical action, it creates another *fait accompli*: a further step towards hell. First, the greenhouse gas (GG) concentration rises further: and most of the greenhouse gases are very long-lived. This is a ratchet, not a dial that can be turned back. Second, all kinds of long-lived equipment and infrastructure are created or maintained that are designed for or naturally suited to high GG emissions (hiGGe). There are hiGGe patterns of settlement – sprawling suburbs and exurbs; hiGGe buildings, poorly insulated, inefficiently heated and cooled; hiGGe machinery, vehicles and electricity generation – using fossil fuels, inefficiently; hiGGe agricultural equipment, using large quantities of fertilizers, pesticides and herbicides, made with fossil fuels. And third, there is a limited range of known technologies on which to draw when making new equipment and infrastructure. That, unlike the GG concentration, will have moved in the right direction – but not as far as it might have.

At some point, we may suppose, the lived reality of climate change will combine with ever-more convincing scientific warnings, to make peoples and therefore policymakers accept the need for urgency. The obvious urgent need will be to replace hiGGe equipment and infrastructure by low – loGGe – alternatives. Even our current limited range of known loGGe technologies allows us to do that. But it does not allow us to do it without initial "fixed" emissions: that is, extra emissions caused by the manufacture and installation of the loGGe equipment.[6] If

[5] The quotation within the quotation was spoken by the oncologist.

[6] As distinct from emissions occurring during operation –" variable" emissions. Fixed emissions include embodied carbon in construction materials (e.g. steel, concrete, fiberglass, silicon), transportation between manufacturing and building sites, and other initial one-time carbon investments (Kenny et al., 2010).

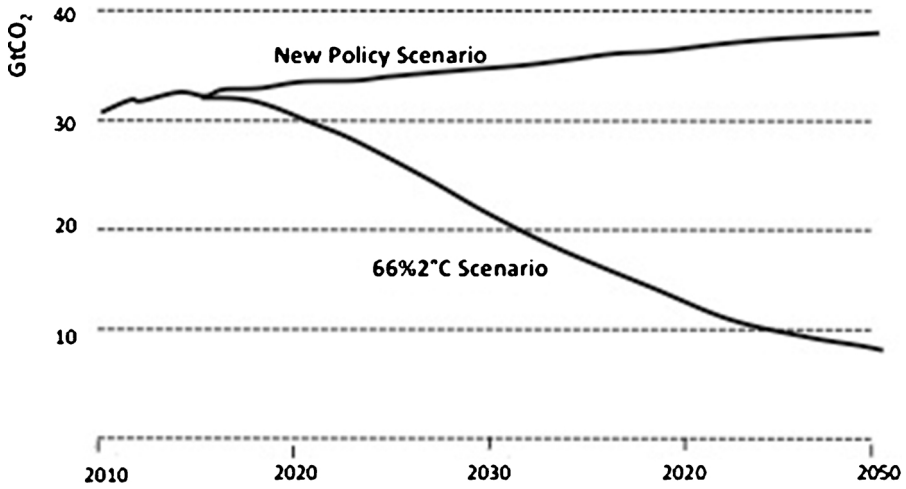

Fig. 1. The gap between scenarios: possible versus necessary.
Source: IEA /IRENA 2017, Figure ES1.

there were little urgency, loGGe equipment would be bought just to replace old hiGGe as this wore out, so the extra fixed loGG emissions would be partially offset by the avoidance of fixed hiGG emissions.[7] But we are assuming urgency, so loGGe equipment has to be bought to replace new, as well as old, hiGGe equipment. Then there must be a substantial increase in fixed emissions – as well as an increased economic burden. The new loGGe equipment, it can be said, incurs a carbon cost in fixed emissions, which it needs to pay back, through carbon mitigation, before it can start to make its net contribution to reducing emissions.

Infrastructure makes the point most clearly. Thus the classic Dutch urban settlement encourages walking, cycling and light rail/trams, while the American suburb or "ex-urb" runs on a multitude of motor vehicles. In the long term it would be desirable to convert the ex-urb to Dutch density and transport modes, but to do it in haste would require much concrete and steel and thus high extra fixed emissions.

4.3. Bio-retro-fitting can solve the fixed emissions problem

Take the example of transport. Suppose that, to *decarbonize* the transport system, we switch at speed to electric vehicles of all kinds; which will be of little use unless they use "renewable" electricity. Consider the fixed emissions cost of new electric vehicles, replacing perfectly functional vehicles that use fossil fuels. Not only will the obsolete vehicles need to be scrapped and replaced, but much of the equipment with which they were produced will be "dedicated" and thus useless for making electric vehicles: it must be replaced too. Likewise coal- and gas-fired power stations will be replaced by wind turbines, solar photovoltaic panels, etc. – and the new equipment required to make *them* …

All this production will carry fixed emission costs, which given the urgency of the switch must be compressed into a short period of time – which for a time defeats the object of reducing the GGe per year. This makes a case for more economy: to allow the "old" vehicles and power stations to operate until they wear out, with some retro-fitting (Steinmueller, 2017). Meanwhile we would build up the new vehicle fleet and power generation infrastructure more slowly. But must that also slow down the cut in GGe, since during this time the old vehicles and power stations will be burning fossil fuels?

Not necessarily. There is an established low-carbon retro-fitted alternative to the fixed emission cost of decarbonizing in a hurry: fuel power stations with wood and biogas; fuel gasoline engines with ethanol and diesels with vegetable oil or biogas.[8] The technical modifications required will be minor and incur small fixed emissions.

Bio-substitution can extend much further. In the construction of buildings, wood can substitute for steel using new cross-lamination technology (Economist, 2012). Wood chips can be used instead of aggregate in the production of concrete, so long as the cement is not calcium silicate but magnesium oxide, which is anyway much lower in GGe (Palmer, 2012). These two uses of wood offer something better than carbon neutrality – carbon capture and storage. Prospects are also good for chemicals: "Technically speaking, the overwhelming share of the total demand for organic chemicals and polymers [accounting for the bulk of emissions from the industry] could be covered from bio-based feedstocks" (Gielen et al., 2008, p. 476).

Unfortunately in solving one problem we would, with present technologies, create another. *With present technologies*, there will be no enormous surplus of biomass production capacity available to be used in this way. The Food and Agriculture Organization estimated in 2010 that the world's agriculture would have to produce 70% more food by 2050 for a population 34% higher, in the face of climate stresses that may well be severe (FAO, 2010). Waste materials, from which the carbon will go back to the atmosphere anyway, can certainly make a major contribution. Thus faeces (farm and human) mixed with other bio-waste can generate large quantities of methane, with high-grade organic fertilizer as by-product (Wikipedia, 2018). Cellulosic waste from crops will yield ethanol – though only with second generation biofuel technologies that are not yet ready; forestry waste can be (is being) formed into wood pellets to replace coal. In this way, indigenous biomass resources could meet up to 44% of UK energy demand by 2050 without impacting food systems (Welfle et al., 2014). But if we go further the effect may be perverse – thus felling forests to feed retro-fitted power stations emits more carbon than is saved in coal (Sterman et al., 2018). So in order to take the opportunities available to substitute for fossil fuels and feedstocks, we shall need a large increase in total global biomass yield: we need to get it without a major cost in fossil fuels for fertilizer, pesticides etc. – and maybe in the face of severe climate stresses. The next section shows how biotechnology may achieve that.

[7] Only partially, because generally loGGe equipment is more expensive in up-front emissions and then saves emissions during its life.

[8] The key constraint for use of methane in vehicles is storage. This has been alleviated by a carbon-fibre tank that increases truck range from 300 to 500 miles. Methane-fueled diesels have low emissions (Hipwell, 2017).

5. Through biotechnology, more and better biomass, more efficiently converted

5.1. The uses of biotechnology in plant breeding, and public opinion on them

Let us first set out the context. We have long had what seemed acceptable means of using energy and growing food, which arose out of, and fed into, Fordism. In effect agriculture became part of a Fordist "industrial complex" when the new dwarf crop varieties of the Green Revolution of the 1960s and 1970s proved able to make lavish use of chemical fertilizers, pesticides, water and machinery (Hazell, 2009). Twin elements of Fordism, synthetic chemistry and mechanical engineering, provide efficient and cheap solutions to a multitude of problems, in agriculture as elsewhere – cheap solutions *as long as fossil fuels and the greenhouse gases and other pollutants they engender, and likewise water and soil, are all priced cheaply, if they are priced at all.* Now none of these seems cheap. The challenge to green biotechnology is to enable farmers and others to use or emit less of all of them while producing larger quantities and higher qualities of biomass.

In the last decade green biotech has acquired the tools to do that job: "The wide-scale adoption of next-generation sequencing technologies has revolutionized the plant sciences… The availability of genomic resources (sequence-based genetic maps and genome and transcriptome sequences) opens up vast possibilities for accelerating the breeding process" (Kantar et al., 2016). What follows in Section 5.2 is a list – far from exhaustive – of developments that are regarded by experts as entirely feasible with the tools now available or becoming available, each of which would increase the yield of major crops substantially. Their impact will be generally additive or even multiplicative.

One institutional obstacle is public, and regulatory, opposition to genetic modification of crop plants and other organisms. This has to be carefully defined. As of 2005 there were essentially three means of plant breeding, all of which in a general sense involved genetic modification:

- *Traditional* – simply combining different varieties and sometimes closely related species.
- *Conventional* – using chemicals, gamma rays and X-rays to induce mutations.
- *Biotechnological* – using biotechnological means to introduce DNA from another organism into a plant cell, in a somewhat imprecise manner, as we have seen.

It is this last method[9] that has met opposition, particularly in Europe and India, and increasingly in China.[10]

All these methods have been improved and accelerated by recent advances in biotechnology. The third has been transformed, and subdivided, by the arrival of CRISPR-Cas9 and similar techniques. One subdivision is using genome editing to do in a carefully targeted manner what conventional mutagenesis does in a random manner: to switch genes on or off, or to move sections of DNA around inside the cell. Likewise it can be used to insert genes from closely related species (cisgenes) close enough for this to be achievable (more slowly) by traditional cross-breeding. These two procedures can be defined as "genome editing without transgenes", and the outcomes could not be distinguished from the outcomes of conventional breeding because they simply are not (or need not be) different. As such they may gain acceptance by those opposed to "genetically modified" (GM) plants.

The other subdivision of biotechnological plant breeding is genome editing with transgenes. This offers the freedom to use genes from whatever organism they may be found in - and the majority of non-human genes whose protein structure is known are bacterial (Economist, 2017a). This freedom might extend to genes artificially created in synthetic biology (see Section 5.5). Genome editing allows transgenes to be inserted in carefully chosen locations. And therefore:

> These new methods will also have regulatory consequences for GM crops. They will, for example, facilitate characterisation of the transgene insert in any one line because the site of insertion will be known, and this will negate the criticism of GM crops that insertion of DNA is currently random with "potentially unforeseeable consequences". In addition, these methods will eliminate the need to introduce a selectable marker gene together with the useful insert of a GM crop. In extreme instances the difference between a targeted GM and an equivalent non-GM line will be as little as a single nucleotide, and the practical distinction between GM and non-GM lines will be blurred. (Baulcombe et al., 2014, p.31)

Nonetheless, opposition to transgenic genome editing will no doubt continue, on the (demonstrably false) assumption that the movement of genes between unrelated species does not occur in nature (Lynas, 2018). (See Section 6.1.)

5.2. Bio-technology and the potential for crop improvement

5.2.1. Initial photosynthesis

Most crop plants use C3 photosynthesis; sugar-cane, sorghum and maize use the more efficient *C4*. Genome editing might switch C3 plants to C4. Both C3 and C4 plants can be otherwise improved (Walker et al., 2016; Kromdijk et al., 2016).

5.2.2. Economy of key inputs

Brackish or salt *water* can be substituted for "good" water if salt-tolerant crop plant (and animal) varieties are developed by genome editing or otherwise. Production in over 30% of irrigated crops and 7% of dryland agriculture worldwide is limited by salinity. A cisgenic "introgression" from a wheat relative into a commercial durum wheat species has increased grain yields on saline soil by 25%; similar developments in other grains are foreseen in the short to medium term (Baulcombe et al., 2014). *Phosphate* can be economized by the development of plants whose seeds do not pass undigested, with phytate, through animal guts (Ely et al., 2014). *Nitrogenous fertilizer* currently uses about 2% of the total energy consumption of mankind – and will not be needed, if the main crop plants are altered to work with symbiotic nitrogen-fixing bacteria, as legumes such as beans already do; likewise some varieties of sugar cane (Warmflash, 2016). *Fish/sea food* as food for other (farmed) fish can be obviated by crop plants genome-edited to contain long-chain omega 3 fatty acids. Camelina has already been given this property transgenically (Baulcombe et al., 2014).

5.2.3. Reduction in crop losses

There are the hazards of *floods*, *drought* and *heat*, which are

[9] Mysteriously, there is no significant opposition to mutagenesis through chemicals, gamma rays or X-rays (Tagliabue, 2017). It may be because this was an established practice before the "green" movement developed. See section 6.1.

[10] Chinese opposition is relatively little known but effective: up to 2013, while China had granted safety certificates for transgenic cotton, papaya, rice and maize, only GM cotton and papaya had been authorised for commercialisation (Ely et al., 2014). I quote from a Chinese army training video (Silent Contest): "The transgene appears to cause no harm to the targeted species, but just uses modern genetic technology to introduce a small improvement in that species. However, this tiny genetic change, no matter how small it may look, not only destroys the full features of the original species, but also places the new species under the control of the entity that introduced the change. The United States has added transgenic food to its national strategic resources. Its push for global adoption is in fact a means for the US to realise its control over the world by controlling global food production. Then, having the same goal, will the US design and implement a 'political transgenic' strategy in the arena of an entire society? The answer for sure is, 'Yes'." (Ely et al., 2014, p.15).

becoming more dangerous with climate change. Flood-tolerant rice has already been developed cisgenically by the International Rice Research Institute; drought and heat are next on its list (Economist, 2014a) (see section 5.5). There is already a drought-tolerant maize (Baulcombe et al., 2014).

Crop pests include *insects*. Insecticidal maize, cotton, poplar and a range of other crops have already been developed transgenically (Klümper and Qaim, 2014).

"Infectious disease is one of the biggest threats to crop production in all environments" (Baulcombe et al., 2014). Resistance to *fungal*, *bacterial* and *viral* diseases can be introduced by modern biotechnology far more quickly than traditional breeding methods. Virus resistance has already been introduced into papaya (Baulcombe et al., 2014).

The most effective protection from *weeds* is provided by herbicides. Herbicide tolerance has been introduced transgenically into soy bean, maize and cotton (Klümper and Qaim, 2014).

Aluminium is a serious problem in the acid soils that comprise 30% of the Earth's ice-free land and makes them toxic to plants. Genes to overexpress malate and citrate – established plant methods for coping with this problem – have been identified (Baulcombe et al., 2014).

Contamination of soil and water by organic and inorganic chemicals is widespread. "In 2014 the [Chinese] government published a national soil survey which showed that 16.1% of all soil and 19.4% of farmland was contaminated by organic and inorganic chemical pollutants and by metals such as lead, cadmium and arsenic" (Economist, 2017c). Microbial remediation is usually optimal for organic chemicals since they can serve as food sources for micro-organisms. Phyto- (plant) remediation is effective for metals, which can be accumulated in leaves and stems and disposed of or extracted and reused. In both cases biobreeding cisgenically or transgenically improves performance (Mosa et al., 2016).

5.2.4. Carbon [capture and] storage

Perennialization achieves substantial carbon storage, besides getting economy of key inputs and reduction in crop losses, compared to annuals. Sugar cane is already perennial, as are oil palms, fruit trees and bushes. "Because of perennials' extended growing season and deep root systems, they may require less fertilizer, help prevent runoff, and be more drought tolerant than annuals. Their production is expected to reduce tillage, which could positively affect biodiversity. Perennial sorghum and perennial rice have already reached the last of four stages of development" (Kantar et al., 2016.) *Algae* might produce up to ten times more than plants in weight of biomass from a given input of sunlight (Global CCS Institute, Parsons Brinckerhoff, 2011). Any significant source of CO_2, particularly in the tropics, could be used to accelerate the growth of algae; genome editing could be used to speed growth and direct biomass production towards high-value chemicals (Nymark et al., 2016).

5.3. Benefits and beneficiaries from crop improvement

The size of impact of future innovations must be uncertain, but we do have meta-studies of the impact of two established "GM" technologies: herbicide tolerance in soy bean, maize and cotton, and insect resistance in cotton and maize:

> On average, GM technology has increased crop yields by 21%… These yield increases are not due to higher genetic yield potential, but to more effective pest control and thus lower crop damage… At the same time, GM crops have reduced pesticide quantity by 37% and pesticide cost by 39%… Average profit gains for GM-adopting farmers are 69%… *Especially smallholder farmers in the tropics and subtropics suffer from considerable pest damage that can be reduced through GM crop adoption*… The profit gains of GM crops are 60 percentage points higher in developing countries than in developed countries… This large difference is due to higher GM yield gains and stronger pesticide cost savings in developing countries. (Klümper and Qaim, 2014; emphasis added)[11]

There is no reason to think that these two plant characteristics are the best-established genetic modifications because they showed the greatest potential for benefit. They simply turned out to be achievable with the limited GM tools available in the 1990s. To take four modifications with obvious huge potential: perennialization and salt tolerance are arriving, or close (see above), while nitrogen-fixation and improved photosynthesis are more challenging. The first three of these may be of particular benefit to farmers in developing countries: perennial crops are protective of the more fragile tropical soils (which face fiercer weather in the tropics), and nitrogen-fixation will free farmers of the cost of nitrogenous fertilizers, which are particularly expensive, or simply unavailable, in Africa (FAO, 2010). In general, smallholders in developing countries have the most to gain from alternatives to Fordist agriculture, because all the Fordist inputs are less available to them (Practical Action, 2017). They are least available to women on smallholdings in developing countries (Practical Action, 2017). Smallholders there also have most to gain from greater availability of biofuels. They often lack grid electricity. Solar and wind energy are suited to small-scale operation in rural areas and can provide cheap off-grid electricity; but the sun goes down and the wind drops, so back-up is needed, which biofuels are ideally suited to providing cheaply (in diesels, for example – see Section 4.3) (Practical Action, 2017).

5.4. Industrial biotechnology can greatly increase the efficiency of conversion of biomass into end products

Industrial (white) biotechnology uses biological systems for the production of chemicals, materials and energy (Soutaert and Vandamme, 2010). Technically, it depends mainly on biocatalysis (the use of enzymes to catalyse chemical reactions) and fermentation (directed use of microorganisms). Biomass provides the preferred starting materials. As such it offers an alternative route to classic "Fordist" chemical engineering, which starts from petrochemical feedstocks and then uses synthetic chemistry, powered by fossil fuels, to create the end product. As already mentioned, petrochemicals could be replaced by turning biomass into the feedstocks that are the basis of synthetic chemistry. That would be to leave out much of the gain from biotechnology. The Dutch chemicals firm DSM shows that one can do better than this by reaching the organic chemical of choice in many fewer steps, saving energy and materials. Instead of a complex 13-step traditional chemical process, one of their plants producing antibiotics now runs a three-step process based on fermentation and enzymes. This has enabled it to cut energy use by 65% and halve raw material costs.[12]

While industrial biotechnology generally starts from biomass, what might be called the "handover point" between what the plant can produce and what the microorganisms can start from, is not defined *a priori*. As pointed out above, algae, some of which have highly efficient ways of using photons to make biomass, could also direct that biomass creation into high-value forms. The fewer the steps in the industrial biotech processes, the better. And *cell-free* biotechnology may increase conversion efficiency further by "stripping molecular biology down to its bare essentials" to keep "the machinery of DNA, RNA, ribosomes and

[11] A later meta-study of the same GM technologies found, in addition, substantial carbon saving, largely through reduced/no tillage cultivation (Brookes and Barfoot, 2017). Part of this arises from carbon storage in roots. And 'genetically resistant crop varieties are the most preferable [control method against infectious diseases], as they do not damage non-target organisms, reduce exposure of farm workers to chemicals, and do not incur CO_2 emissions from applications of chemicals by tractors' (Baulcombe et al., 2014).

[12] http://www.dsm.com/en_US/cworld/public/media/downloads/publications/backgrounder_bio_based_economy.pdf. Accessed 17 February 2014.

proteins, which can be engineered to make useful chemicals, ranging from drugs to the building-blocks of plastics… [but]… to get rid of the bags that contain it… [so that]… no biochemical effort is wasted on running, growing or dividing any actual cells" (Economist, 2017b).

Given that white biotech saves on fossil fuels as sources both of feedstocks and of process energy, it has great potential for reducing GGe. And there's the rub for its diffusion: the costs it saves depend greatly on the market prices of those fossil fuels, and thus its profitability stands at the mercy of their fluctuations. When oil and gas prices are high, white biotech will pay; while they are low, its economics are much less attractive. Only add a carbon price to the producer's price of oil or gas, and industrial biotechnology will reveal its full potential; all the more because it operates in closed systems (inside tanks, to put it simply) and thus its innovations are largely exempt from public opposition.

5.5. Biotechnology, fixed emissions and diffusion

It can be seen from the discussion of fixed emissions that the problematic technologies are those that are embodied in *dedicated* equipment, infrastructure and machinery. Thus in order to build and install a new wind turbine and thus save fossil fuel, a great deal of fossil fuel has to be spent on steel and cement and much else. But once we have developed, let us say, perennial and nitrogen-fixing wheat, to get a field full of it and thus start to save on various GG emissions will require very little expense of fossil fuel: just use the grain produced on a small area of land the year before, to sow a whole field. The new technology is embodied in the plant itself, nothing more. Biology is almost as good at replicating a new organism as ICT is at replicating a piece of software. The farmers need tractors and barns etc. – but they have those already. The problem of fixed emissions in diffusing new plant varieties is therefore small. In industrial biotechnology the problem may be modest for similar reasons. Much of the initial cost inheres in the research and development, including that of genetically modified microorganisms, which can be replicated a great deal faster and thus even more cheaply than plants. The catalysing enzymes in effect partly replace equipment, since they need fewer process steps than synthetic chemical engineering.

Fixed emissions need not obstruct the diffusion of new organisms, then. Of course there is much else that might, as the extensive literature on diffusion shows. But let us begin with an example, of flood-tolerant rice. The genome of rice is the smallest of the main grain crops, and it was the first to be sequenced, in 2005. International Rice Research Institute (IRRI) researchers were then able to enhance their (non-transgenic) breeding methods with "marker-assisted back-crossing" that allowed much faster breeding-in of valuable traits found in unusual rice strains. Flood-tolerant rice was the first fruit of this advance: it went from experimental use in 2008 to being planted, in some 12 different varieties, by five million farmers across the world five years later (Economist, 2014a).

Five years from development to widespread diffusion. What, following the literature of diffusion, can account for this remarkable speed? First, of course, potential adopters evaluate an innovation on its relative advantage (Rogers, 2003). Any rice farmer could appreciate the advantage from a variety that would survive floods in good shape when existing varieties would die after two weeks under water; when the survivor would have the advantage of plentiful water following the floods. Risk aversion normally works against innovation; scarcely against this one. But why would the innovators – the first adopters in each community – be confident in advance that the new variety would perform as promised? Largely because the IRRI said so – and the IRRI, a non-profit organization, had brought their fathers or grandfathers the Green Revolution in the 1960s and' 70 s.

Another factor spurring fast diffusion of the flood-resistant rice varieties may well have been the context in terms of yields. Rice yields in Asia were rising at scarcely 1% a year by 2013, a long way down from the years of the Green Revolution. In some areas they were falling (Economist, 2014a). Innovations are more attractive to those whom they promise to save from dearth, than to those who are becoming steadily more affluent anyway. As climate change takes hold, the alternative to innovation will not be the continuation of a comfortable status quo. Another factor encouraging fast adoption in future should be the internet: it augments the social networks that spread trusted information about the innovation (Strang and Soule, 1998). Seeing is believing, and believing is also easier when the early adopters use a micro-blog (Huang and Sun, 2014) to explain what they did and what they got.

We cannot, on the other hand, count on *development* as rapid as that of flood-tolerant rice, which was made easier by the fact that a flood-tolerant rice existed already. But, looking ahead, there is an advantage in drawing on a general purpose technology. The greatest interest in the fruits of biotechnology – absent carbon pricing – is shown, for now, on the biopharma and biomedicine side. But general advances such as gene editing are of equal value for plant breeding. The same applies to synthetic biology. "Synthetic biology applies the knowledge and tools developed in analytical biology to synthesise biological entities… drawing on expertise in molecular biology, computer science, chemistry, and engineering" (Nuffield Council on Bioethics, 2012, p.59).

Here again is a (developing) body of general technological competences drawing heavily on ICT. The money now is mostly on the medical side: e.g. engineer a phage (virus) to knock out drug-resistant staphyllococci (Nuffield Council on Bioethics, 2012). But general competences built in one sector can be switched to another: "Once synthetic biology has been developed, there is the potential for developing more complex novel traits in plants, including the production of novel compounds for biofuels or industrial biotechnology" (Baulcombe et al., 2014, p.35). A key step along the way has been the design of an artificial yeast genome, announced in March 2017 (Richardson et al., 2017). Yeasts are industrial workhorses, as with beer and bread, so the economic impact of this development should be large – for example, yeast-made milk may use 98% less water and require up to 91% less land than cow's milk (Zaraska, 2017).

6. Discussion and conclusion

6.1. Fear, danger and regulation

It follows from the foregoing arguments that certain fears regarding the development of green biotechnology are overblown: there is no simple binary in plant (or other) breeding, of "traditional" (good, safe) versus "biotechnological, GM" (bad, dangerous). There may be particular risks in making untargeted mutations in genomes, but that applies to chemical and nuclear mutagenesis (which have been ignored by those against "GM") as well as biotechnological genetic modification. Now it is the biotechnological modification – through genome editing by CRISPR et al. – that has the advantage of increasingly precise and accurate targeting (Baulcombe et al., 2014). Moreover, entirely against stereotype, it is small farmers in developing economies who, on the evidence so far, have most to gain from biotechnology applied to plant breeding, transgenes included. White biotechnology is not suspect. So biotechnology, green and white, offers, among other good things, relatively safe mitigation of climate change.

This view is not generally held by "public opinion". "Informed opinion" and "public opinion" diverge greatly here:

> The results of our global stakeholder survey on biotechnology and climate change reveal a rather positive assessment of the role of biotechnology in addressing climate change problems… [However] the few respondents who expressed radical opposition to the use of biotechnology to address climate change problems represented those stakeholders who were considered to be most influential in the biotechnology debate, the climate change debate, the formation of

> public opinion and in political decision making processes… These powerful stakeholders represent professional international advocacy groups who are publicly associated with environmental justice and are therefore trusted to act in the public interest. This may help explain why the potential of biotechnology to address climate change challenges may be privately acknowledged but is hardly ever mentioned in national and international environmental debates and policy reports. *Biotechnology may not be "clean tech" as long as powerful environmental groups say it is not… it is politics rather than independent risk assessments or empirical evidence from the field that determines whether biotechnology is being used to tackle climate change challenges*. (Aerni et al., 2016, p.26; emphasis added)

Politics has determined that all new GM varieties (genetically modified by *biotechnology*) be subject to specific regulatory procedures before they can be approved for use. In the European Union only one such has been approved since 1998 – while GM varieties modified by chemical or nuclear mutagenesis need no such approval (Tagliabue, 2017). In the United States the problem is rather delay and expense. Normally regulatory processes speed up as they become familiar. However since 1998 the average time taken by the regulatory process has been stable around 6–7 years, having been barely half that before 1998. The average cost of the process in 2008–12 was US$35.01 million, 25.8% of the total cost of GM introduction (Smart et al., 2017). That may seem modest, but the combined effect of expense, delay and uncertainty is to deter almost all but the largest private firms (Smart et al., 2017). The rest, private and public, are free to go on with chemical and nuclear genome-smashing.

There may be a dialectical perfect storm at work here: *neoliberal thesis* – the profit motive must rule; almost anything must be patentable with a view to profit. *Environmentalist antithesis* – we do not trust the products of profit-seeking capitalists who want to own new life-forms. *Synthesis* – profit from the safer new life-forms is reserved to the strongest capitalists, who continue to serve as useful demons for environmentalist fund-raising.[13]

This is not to dismiss the dangers of new organisms created even with good intent, let alone those intended to cause harm. Regulation – drawing on *independent risk assessments and empirical evidence from the field*, to quote from Aerni et al. above – is needed in order to deal with these dangers. This may be particularly fraught in two overlapping areas: DIYbio and developing economies. For better or for worse – no doubt for both – DIYbio is on the rise: as was pointed out above, the movement around it is making already cheap tools and simple procedures cheaper and simpler. This may assist the wide diffusion of competences in plant breeding, among other areas. We have some indication where this might lead, from the history of Bt cotton in India. Bt cotton (genetically modified with an insecticidal transgene from *Bacillus thuringiensis*) was developed by, and thus belonged to, Monsanto. Monsanto's Indian subsidiary officially released it on the Indian market in 2002, but it was being grown there illegally already: "By 2005 it was estimated that 2.5 million hectares were under 'unofficial' Bt cotton, twice the acreage as under the ones that had been sown from Monsanto's packets… a veritable cottage industry had sprung up… whereby small-scale breeders were crossing reliable local varieties with the caterpillar-proof Bt plant… The world's first GM landraces had arrived" (Kingsbury, 2009, p.417).

The Indian farmers no doubt appreciated the savings in money and the reduction in harm from spraying less pesticide, as well as the increase in yield. (See Klümper and Qaim, 2014, quoted in section 5.3.) But the most interesting agents of change here were the "small-scale breeders" in India. At the time, all they could do was to take the products of someone else's transgenic breeding, without permission, and improve them in a rather traditional way. In a few years they may be able to do some transgenic breeding themselves – perhaps with the help of biohackers in the advanced world, perhaps without.

So how will the biohackers of the advanced and developing world use their new competences? And how should they be controlled?

> In America biohackers used to risk getting arrested, but in recent years the FBI has opted for a more enlightened approach: local special agents talk to community labs; the agency organises an annual DIYbio conference… "The people who practise DIYbio are best placed to know what is going on," says Edward You, who pioneered the FBI's effort… As DIYbio grows calls for tighter regulations will get louder. Yet clamping down would be counter-productive, argues Mr Carlson [a founder of DIYbio]. Such rules would be hard to enforce and drive biohackers underground…. Much better… for governments to support community labs where everybody…..can experiment openly and safely. (Economist, 2014b)

DIYbio *may* already have shown the way. The following quotation can show, at least, the direction in which it should be encouraged to go:

> The DIYBio movement has developed an alternative practice-based ethics, which complements the ethics procedures within traditional academia. The DIY biologist approach seems well suited at producing a robust public dialogue, resulting in safe and responsible research… DIYBio practitioners explore ethical issues in a broader perspective, signal ethical issues earlier, and signal different issues… the DIYBio community has been progressive in developing Codes of Ethics to guide the activity of the movement and promote experimentation based on shared principles of transparency, safety, and open access. DIYBio projects have the ability to organise moral deliberation, indirectly and directly, and not just as a means to restore trust in science or communicate science… Discussing ethics, parallel to other DIYBio efforts, is empowering in the sense that it enhances the collective and individual capacity to morally assess biotechnological developments and issues. (DITOs Consortium, 2017)

6.2. Conclusion

The value of biomedicine –red biotechnology – is rather obvious. We do not need some far-reaching institutional reform to make us ready to pay, for example, for new viro-therapies to kill cancer cells. And our readiness increases as our affluence does, and we wish to be spared such illness as will make affluence meaningless. The value of green and white biotechnology has been less obvious.

Enter climate change, and the tables are turned. Red biotechnology has vast potential; but we do not need it to give most of us and our descendants good prospects of living in reasonable health to seventy or eighty. We do need some stability in the climate. Those many applications of green and white biotechnology that can help towards it will soon be very valuable indeed. That is, they will be very valuable to society; to make them profitable will require institutional reform.

We have now seen the maturing of biotechnology with genomics, proteomics and genome editing, to the point where it can take its place alongside ICT as a new techno-economic paradigm. This paper has set out a number of institutional changes that are required to release its potential, distinguishing between those most relevant to biomedicine and those key to industrial biotechnology and plant breeding (etc.). Biomedicine needs better direction of public investment, patent reform, new ways of paying for drugs, and compulsory publication of clinical data. The other areas need carbon taxation or other carbon pricing, pricing of greenhouse emissions generally, of pollution generally, and of water use. Plant breeding also needs a change in the stance, or a reduction in the influence, of powerful environmental groups. Industrial biotechnology and plant breeding are key to mitigating (and adapting to) climate change, and so these institutional changes would

[13] A blow against this misfortune has been struck by the brave and brilliant recantation of the anti-GM activist Mark Lynas in *Seeds of Science* (2018).

engage enormous effort in the innovation and diffusion of the appropriate applications of biotechnology. Through bio-substitution in (for example) transport equipment, power generation, chemicals and construction, they can take the influence of biotechnology far beyond its current bounds.

The arguments of this paper are thus consistent with those of Perez and Tylecote in the 1980s and' 90s: the potential of a new techno-economic paradigm to drive the world economy can only be released by institutional reforms. In their absence the ICT paradigm that has prevailed for some 20 years has been applied and diffused in a limited and distorted way that has increased global inequality and dampened world demand. Notably, in the absence of carbon pricing it has not been applied heavily to resource saving. When biotechnology is so applied, it will have good effects not only on the climate. Fossil fuels are largely owned or controlled by the rich and powerful and produced and used mostly on a large scale: we shall see them replaced as main sources of energy and materials by solar, biomass and wind, all naturally small-scale and mutually supportive. This will have an equalizing effect, worldwide, and a demand-increasing one, as rents received by rich people for doing nothing are replaced by earnings of poor people for doing something with locally produced biomass and renewable energy.

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